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Temperature Field Simulation of Wire Electrode in High-speed and Medium-speed WEDM under Moving Heat Source

Xiaodong Yang^{a*}, Guanglei Feng^a, Qing Teng^a^aHarbin Institute of Technology, P.O. 421, 92, West DaZhi Street, Nangang District, Harbin 150001, China* Corresponding author. Tel.: +86-451-86417672; fax: +86-451-86413485. E-mail address: xdyang@hit.edu.cn**Abstract**

The high-speed and medium-speed wire electrical discharge machines which are originally developed in China are playing an important role in mold making. However, the wire electrode wear is a universal problem in the machining process because the wire electrode is used repeatedly. Considering the relative motion between the wire electrode and the workpiece, the heat transfer model of wire electrode under moving heat source was established, and the temperature field of wire electrode was simulated in single pulse discharge by FEM. The results indicated that the size of the melted zone along the wire electrode axial direction increased remarkably while the depth size, the width size and the volume of the melted zone reduced apparently when the wire running speed increased. It can be concluded that the high relative speed between the wire electrode and the workpiece is beneficial to reduce the wire electrode wear in radial direction. Furthermore, when the wire running speed is higher than a certain value, the discharge column will slide over the wire electrode surface before the wire material reaches its melting point, thus the melting and ablation of the wire electrode material does not happen, which can almost realize no wire electrode wear.

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Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).**Keywords:** Wire electrical discharge machining (WEDM); Temperature Field; Wire running speed; moving heat source; wire electrode wear**1. Introduction**

In wire electrical discharge machining (WEDM), the continuous moving wire is used as tool electrode to remove workpiece material by the pulse electrical discharge in the gap between the workpiece and the wire electrode. In China, according to the wire running speed, WEDM machines can be divided into high-speed, medium-speed and low-speed WEDM machines. The high-speed WEDM machine is originally developed in China. Its wire electrode makes reciprocating movement with high-speed of 8 to 10 m/s and can be used repeatedly. It can obtain higher machining speed with lower cost. In recent years, the medium-speed WEDM machine which is originally developed from the high-speed WEDM machine is getting more and more attention in China due to its multiple-cutting function which enables both rough and finish cutting. Both in high-speed and in medium-speed WEDM, because the

wire electrode is used repeatedly, the wire electrode wear will affect the machine precision and reduce the service life of wire electrode.

WEDM is a thermal process. Thermal energy generated by a pulse discharge between the workpiece and wire electrode results in melting and evaporation followed by material removal of both the workpiece and wire electrode. The material removal of wire electrode results in the wire electrode wear. To investigate the thermal transfer process, numerous attempts have been made to calculate temperature distribution in electrodes based on the heat transfer theory by using the finite element method [1-4]. In these studies however, the heat sources of discharge spots were assumed to be static and the influence of relative motion between wire electrode and workpiece on the temperature field was ignored. Kunieda et al. carried out EDM experiments using a rotating disc electrode to obtain the relative sliding motion between electrodes and found that the arc column slides more easily on the cathode than on the

anode [5,6]. Considering the high-speed relative movement between the wire electrode and workpiece in the high-speed and medium-speed WEDM, this paper establishes a heat transfer model of the wire electrode under the moving heat source to analyze the wire electrode wear. The temperature field on the wire electrode surface under the single pulse discharge conditions was simulated by the finite element method. Then, the influence of wire running speed on the wire electrode wear was investigated.

2. Heat transfer model of the wire electrode under the moving heat source

2.1. Sliding of arc column

In WEDM, the wire electrode is connected to the cathode of pulse power supply. According to the conclusions of Kunieda et al. [5,6], it can be inferred that the arc column will slide on the wire electrode surface during the discharge duration in the high-speed and medium-speed WEDM. Thus, verification experiments were conducted. Under the conditions showed in Table 1, discharge was generated consecutively for several seconds with the stationary wire electrode and the high-speed running wire electrode separately, and discharge craters generated on the wire electrode were measured using a laser confocal microscope (Olympus OLS3000). Measured results are shown in Fig.1. It can be found that when the wire running speed is 10m/s, the discharge crater is significantly elongated and its depth decreased indicating that the arc column slid on the wire electrode surface as shown in Fig.2 (the discharge crater on the workpiece surface is not shown for simplicity). It can be also found that the length of discharge crater is about 300 μ m which is approximately equal to half of the product of wire running speed and pulse duration. Hence

Table 1. Machining conditions

| | |
|---------------------------|---------------------|
| Open voltage (V) | 110 |
| Discharge voltage (V) | 25 |
| Peak current (A) | 3.2 |
| Pulse duration (μ s) | 60 |
| Wire running speed (m/s) | 10 |
| Wire electrode | Mo (Φ 0.18mm) |
| Workpiece | Steel |
| Dielectric | Emulsion |
| polarity | workpiece : + |

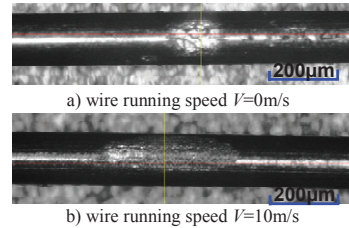


Fig. 1. Discharge crater on wire electrode surface

in this study, the equation $L=0.5t_{on}V$ was used to calculate the sliding distance of arc column on the surface of the wire electrode during the single pulse duration, where L is the sliding distance (m), t_{on} is the pulse duration (s) and V is the wire running speed (m/s).

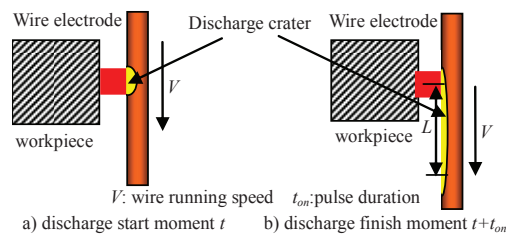


Fig.2 Concept of arc column sliding on wire electrode surface

2.2. Heat source

When the voltage applied on the gap between the electrodes overcomes the dielectric breakdown strength of the gap, a channel of plasma will be formed between the electrodes. Most of the discharge energy is distributed into the electrodes and the discharge gap as thermal energy. The heat flux density on the electrodes surface follows the Gaussian distribution as,

$$q(r) = \frac{3}{\pi R^2(t)} \eta UI \exp\left(-\frac{3r^2}{R^2(t)}\right) \quad (1)$$

where, $q(r)$ is the heat flux density at the radius of r , $R(t)$ is the radius of the arc column at the moment of t , η is the energy distribution coefficient, U is the open voltage applied on the gap and I is the peak current.

In this study, the energy distribution coefficient was determined based on the conclusion that the energy distribution to anode and cathode is different, about 48% and 34% respectively [7]. Kunieda et al [8] found that the arc plasma completed expansion within 2 μ s after dielectric breakdown, and thereafter, its diameter remained constant during discharge. In this research, since 2 μ s is rather shorter than the discharge duration of 60 μ s used in this research, the diameter of arc column was regarded as constant for simplicity, and was estimated according to the peak current and the pulse duration based on experience.

2.3. Heat transfer model of wire electrode

In WEDM, the heat source was assumed to move along the length direction of wire electrode at a constant speed on the wire electrode surface. For simplicity, the wire electrode was taken as a semi-infinite solid and the heat transfer model of wire electrode under the moving heat source was built as shown in Fig.3. The wire electrode surface passed by the moving heat source is set as the active surface, and the non-active surface is supposed to be adiabatic.

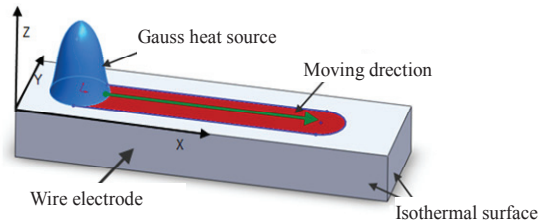


Fig.3. Wire electrode heat transfer model under moving heat source

The WEDM temperature field under moving heat source is transient, which belongs to the unsteady heat transfer problems. According to the principle of superposition, the moving heat source can be regarded as the combined action of infinite transient fixed heat source at different time and different locations. Based on the Fourier heat transfer theory, the transient heat transfer model in Cartesian coordinate system under fixed heat source is expressed as,

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (2)$$

where, x , y and z are the coordinates in Cartesian coordinate system, T is temperature ($^{\circ}\text{C}$), λ is the thermal conductivity of the wire electrode material ($\text{J}/(\text{m}\cdot\text{s}\cdot\text{K})$), ρ is the density of the wire electrode material (kg/m^3), c is the specific heat of the wire electrode material ($\text{J}/(\text{kg}\cdot\text{K})$) and t is the time (s).

The heat transfer model of wire electrode under the moving heat source can be calculated by coordinate transformation. It is assumed that the heat source moves along the X axis direction at a speed u . With a moving coordinate system, if its origin is set at the position where the heat source acts, then a point $P(x, y, z)$ in the fixed coordinate system at any time can be transformed to the point $P(\xi, y, z)$ in the moving coordinate system, where, $\xi = x - ut$. Therefore, the heat transfer model in the moving coordinate system is converted to,

$$-u \frac{\partial T}{\partial \xi} = \frac{\lambda}{\rho c} \left(\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (3)$$

After the temperature distributions in the moving coordinate system are transformed to the ones in the fixed coordinate system, the temperature distribution under the moving heat source can be obtained by the linear superposition of several instantaneous fixed heat sources acting at different moments and different locations according to the superposition principle.

3. Finite element simulation results of wire electrode temperature field

The three-dimensional temperature field in the wire electrode under the single pulse discharge was simulated using ANSYS. The material of the wire electrode was molybdenum. Since the thermal conductivity and the specific heat capacity of molybdenum are temperature dependent, they were calculated by linear interpolation or extrapolation according to the given thermal conductivity and specific heat capacity under different temperatures. Table 2 shows the simulation conditions, in which the wire electrode with zero-running speed represents the fixed heat source condition.

Table 2. Simulation conditions

| | |
|---------------------------------|---------------|
| Open voltage(V) | 110 |
| Discharge voltage(V) | 25 |
| Peak current(A) | 3 |
| Pulse duration(μs) | 60 |
| Wire running speed(m/s) | 0、6、10、20、25 |
| Wire electrode | Mo |
| Workpiece | Steel |
| Polarity | workpiece : + |

3.1. Wire electrode temperature field

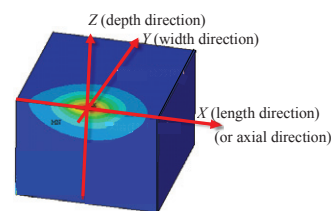


Fig.4. Measurement direction of wire electrode melting zone

As shown in Fig.4, to represent the wire electrode melting zone conveniently, the X axis, Y axis and Z axis was defined as the length direction or the axial direction of the wire electrode (which is the heat source moving direction under the moving heat source), the width direction, and the depth direction, respectively.

Fig.5a) shows the wire electrode temperature field under the fixed heat source in single pulse discharge. As the Gaussian heat source is axisymmetric, the figure

only shows half of the wire electrode subdivision graph along the wire running direction. It can be found that isotherms in the wire electrode heated zone are ellipsoid surfaces which are concentric with the centre of arc column. From the simulation results, it was found that width and length of the melting zone are $16.7\mu\text{m}$ and depth of the melting zone are $10.4\mu\text{m}$.

In the moving heat source, when the heat source passes over a certain point on the wire electrode, its temperature peaks at a certain moment. Therefore, the wire electrode temperature field was obtained from the superposition of the highest attainable temperature at different positions on the wire electrode during the discharge duration. Fig.5b) shows the wire electrode temperature field under the moving heat source in a single pulse discharge with the wire running speed of 10m/s .

Fig.6 shows the top view and cross section of the wire electrode melted zone obtained from the superposition of the highest attainable temperature method. For comparison, the wire electrode melted zone profile under the fixed heat source ($V=0\text{m/s}$) is presented with the

circle and semicircle arc. Here the 0 position in Fig.6 indicates the position of the fixed heat source and the initial position of the moving heat source. It was found that when the wire electrode ran at a high speed of 10m/s , the size of the melted zone reduced significantly and the maximum width and depth was $9.0\mu\text{m}$ and $4.2\mu\text{m}$, respectively. In contrast, the size of the melted zone along the length direction of wire was markedly stretched up to $330\mu\text{m}$ as shown in Fig.6, which is approximately equal to half of the product of the discharge duration and the wire running speed. It was also found that both width and depth of the melted zone increased gradually along the wire axis and peaked at the terminal point of the moving heat source where the discharge was extinguished. This is because along with the continuous sliding of the heat source on the wire electrode, the initial temperature of the heated position on the wire electrode gradually increases, resulting in continuous expanding of the melting zone.

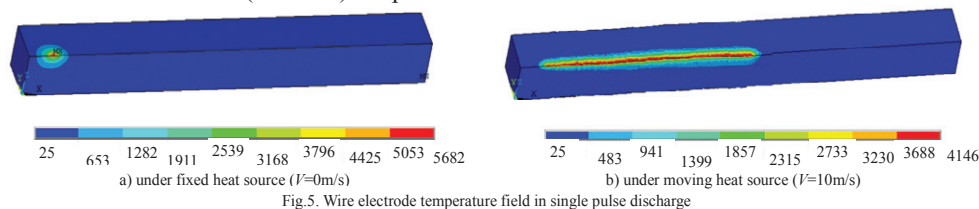


Fig.5. Wire electrode temperature field in single pulse discharge

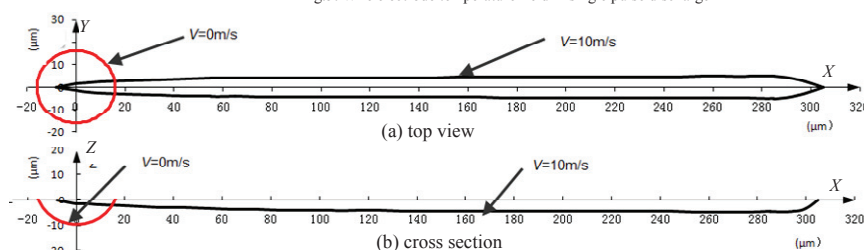


Fig.6. Wire electrode melting zone profile under moving heat source

Fig.7 shows the wire electrode temperature in width and depth direction under $V=0\text{m/s}$ and $V=10\text{m/s}$ at the discharge finish moment. Fig.7(a)-(b) shows the point where the fixed heat source acts, and Fig.7(c)-(d) shows the terminal point of the moving heat source. It can be found that the zone where temperature is over the melting point (2610°C) of Mo under the moving heat source is significantly smaller than that under the fixed heat source.

3.2. The Influence of wire running speed on the wire electrode temperature field

Fig.8 shows the relationship between the maximum width of the wire electrode melted zone and the wire running speed. Fig.9 shows the relationship between the maximum depth of the wire electrode melted zone and

the wire running speed. Fig.10 shows the relationship between the length of the wire electrode melted zone and the wire running speed. It was found that the higher the wire running speed is, the smaller width and depth of the wire melted zone, and the longer length of the melting zone is (except the wire running speed of 30m/s). This is because when the wire running speed increases, the sliding speed of the arc column relative to the wire increases, while the time of the arc column or the heat source dwelling on the wire surface decreases, leading to the decrease of heat flux density on the wire electrode surface, thus the size of wire electrode melted zone along the width and depth direction reduces. Fig.11 shows the relationship between the melted zone volume of the wire electrode and the wire running speed. It can be seen that the melted zone volume increases once and starts decreasing with increasing the wire running speed.

The wire electrode radial wear depends on the product of the removal volume in the single pulse discharge, total discharge times and wire electrode length. Thus, the increase of the wire running speed results in the decrease of the melted zone volume, and the wire electrode radial wear can be reduced. Therefore, both the machining precision and service life of the wire electrode are improved. It also verifies the reason why the wire electrode can be used repeatedly in high-speed and in medium-speed WEDM. Fig. 12 shows the highest attainable temperatures of heated region on the wire

electrode at different wire running speeds. It can be found that the highest attainable temperature of heated region on the wire electrode decreases as the wire running speed increases. When the wire running speed reaches 30m/s, the highest attainable temperature on the wire electrode surface is 2518°C, which appeared at the discharge finish moment and it is lower than the melting point of Mo indicating the melting zone on the wire electrode surface will disappear, and the wire electrode wear can be almost zero.

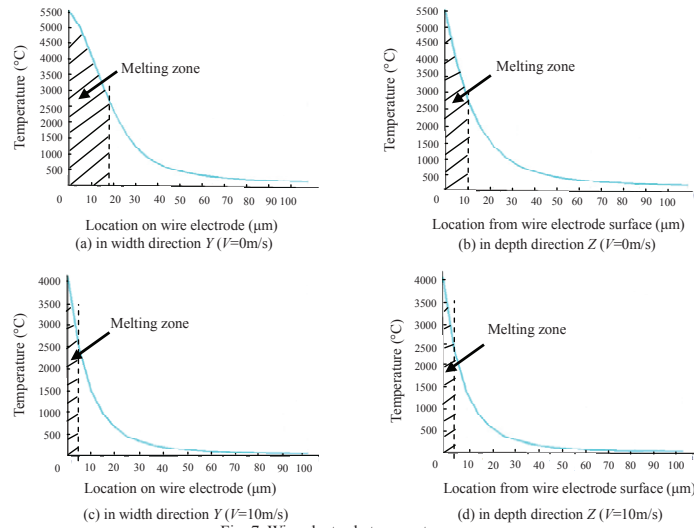


Fig. 7. Wire electrode temperature

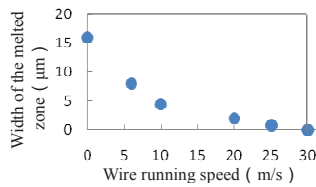


Fig. 8. Relationship between melted zone width and wire running speed

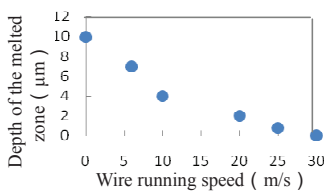


Fig. 9. Relationship between melted zone depth and wire running speed

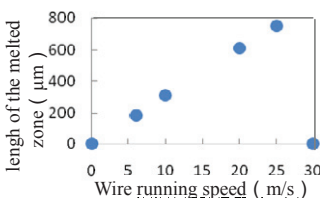


Fig. 10. Relationship between melted zone length and wire running speed

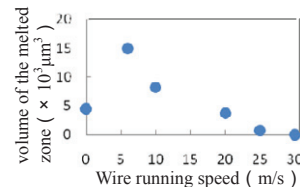


Fig. 11. Relationship between melted zone volume and wire running speed

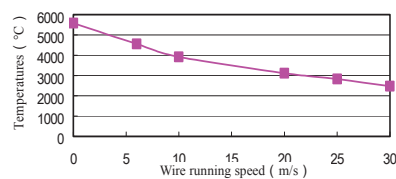


Fig. 12. Relationship between the highest temperature of heated region on wire electrode wire and wire running speed

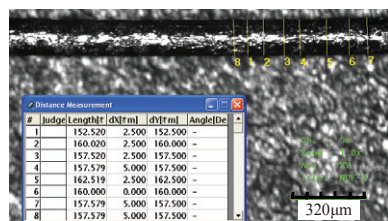
4. Experimental investigation of influence of wire running speed on wire electrode wear

To verify the influence of the wire running speed on wire electrode wear experimentally, wire electrode diameter was measured after machining under different wire running speeds. The experiment was carried out

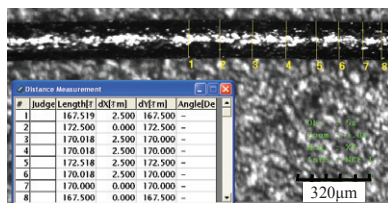
using a high-speed wire electrical discharge machine (Sanguang DK7740-P) under the machining conditions shown in Table 3, and the wire running speed was set to $V=5.8\text{m/s}$ and $V=11.6\text{m/s}$. After finishing the area of 14616mm^2 with a depth of cut of 7mm , the wire electrode diameter was measured using a laser confocal microscope (Olympus OLS3000). The measurement results are shown in Fig.13. It was found that the wire electrode average diameter after machining at $V=5.8\text{m/s}$ and 11.6m/s were $\Phi 157\mu\text{m}$ and $\Phi 170\mu\text{m}$, so the wire electrode wear in diameter direction were $23\mu\text{m}$ and $10\mu\text{m}$, respectively, indicating higher wire running speed is useful for reducing the wire electrode wear significantly.

Table 3. Machining conditions

| | |
|---------------------------------|---------------------------------|
| Open voltage(V) | 110 |
| Discharge voltage(V) | 25 |
| Peak current(A) | 20 |
| Pulse duration(μs) | 32 |
| Wire running speed(m/s) | 5.8, 11.6 |
| Wire electrode | Mo ($\Phi 0.18\text{mm}$) |
| Workpiece | Steel (thickness 7mm) |
| Dielectric | Emulsion |
| polarity | workpiece : + |



(a) $V=5.8\text{m/s}$



(b) $V=11.6\text{m/s}$

Fig.13. Wire electrode wear under different wire running speeds

5. Conclusions

In this research, the heat transfer model of the wire electrode under the moving heat source was established. The wire electrode temperature field in single pulse discharge condition was simulated using finite element analysis and the influence of the wire running speed on wire electrode wear was investigated. The following conclusions were obtained:

When the wire running speed increases, the sliding speed of the arc column relative to the wire electrode surface increases, while the time of the arc column or the heat source dwelling on the wire surface decreases, leading to the decrease of heat flux density on the wire electrode surface, thus the wire electrode melting zone along the width and depth direction is reduced while the wire axial direction is lengthened obviously.

In high-speed and medium-speed WEDM, the increase of the wire running speed results in the decrease of the melted zone volume, and the wire electrode radial wear can be reduced. Therefore, both the machining precision and service life of the wire electrode are improved. This fact explains theoretically the reason why the wire electrode can be used repeatedly in high-speed and medium-speed WEDM.

When the wire speed exceeds a certain value, the arc column can slide over the wire electrode surface before the wire electrode surface temperature reaches its melting point, thus no electrode material is molten or removed and the wire electrode wear can be almost zero.

Acknowledgements

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